Shot noise and reconstruction of the acoustic peak

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We study the effect of noise in the density field, such as would arise from a finite number density of tracers, on reconstruction of the acoustic peak within the context of Lagrangian perturbation theory. Reconstruction performs better when the density field is determined from denser tracers, but the gains saturate at $\bar{n} \sim 10^{-4}\,(h\,\mathrm{Mpc}^{-1})^3$. For low density tracers it is best to use a large smoothing scale to define the shifts, but the optimum is very broad.

I. INTRODUCTION

Baryon acoustic oscillations (BAO) in the baryon-photon fluid provide a standard ruler to constrain the expansion of the Universe and have become an integral part of current and next-generation dark energy experiments [1]. These sound waves imprint an almost harmonic series of peaks in the power spectrum $P(k)$, corresponding to a feature in the correlation function $\xi(r)$ at $\sim$100 Mpc, with width $\sim$ 10% due to Silk damping [2–7]. Non-linear evolution leads to a damping of the oscillations on small scales [6, 8] (and a small shift in their positions [9–13]),

$$P_{\rm obs}(k) = b^2 e^{-k^2\Sigma^2/2} P_L(k) + \cdots\cdots \tag{1}$$

where we have assumed a scale-independent bias, b, and left all broad band and mode-coupling features implicit in the $\cdots$. The damping of the linear power spectrum (or equivalently the smoothing of the correlation function) reduces the contrast of the feature and the precision with which the size of ruler may be measured and is given by the mean-squared Zel'dovich displacement of particles,

$$\Sigma^2 = \frac{1}{3\pi^2}\int dp\ P_L(p) \qquad . \tag{2}$$

In [14] a method was introduced for reducing the damping, sharpening the feature in configuration space or restoring the higher k oscillations in Fourier space. This procedure was studied in [15, 16] using Lagrangian perturbation theory. In this brief note we generalize these treatements to show how the effects of noise in the density field, arising for example from the finite number density of tracers, affects reconstruction. We shall concentrate on the broadening of the peak, and refer the reader to [15, 16] for details, discussion and notation.

II. RECONSTRUCTION WITH NOISE

The prescription of [14] begins by smoothing the observed density field to filter out high k modes: $\delta(\mathbf{k}) \to \mathcal{S}(k)\delta(\mathbf{k})$. We shall take $\mathcal{S}$ to be Gaussian of width R. From the smoothed field the negative Zel'dovich displacement is computed $\mathbf{s}(\mathbf{k}) \equiv -i(\mathbf{k}/k^2)\mathcal{S}(k)\delta(\mathbf{k})$. Then the objects are shifted $\mathbf{s}$ to form the "displaced" density field, δ_d, and an initially spatially uniform grid of particles is also shifted to form the "shifted" density field, $\delta_s(\mathbf{k})$. The reconstructed density field is defined as $\delta_{\rm recon} \equiv \delta_d - \delta_s$, and to lowest order it is equal to the linear density field [14–16]. The non-linear damping is however modified from $\exp[-k^2\Sigma^2/2]$ to [15, 16]

$$\begin{aligned} D(k) \ &\equiv\ \mathcal{S}^2(k)e^{-\frac{1}{2}k^2\Sigma_{ss}^2} + [1-\mathcal{S}(k)]^2 e^{-\frac{1}{2}k^2\Sigma_{dd}^2} \\ &+\ 2\mathcal{S}(k)[1-\mathcal{S}(k)]e^{-\frac{1}{2}k^2\Sigma_{sd}^2}\ . \end{aligned} \tag{3}$$

with Σ_{ss} and Σ_{dd} defined as integrals over the linear power spectrum, P_L, (see below) and $\Sigma_{sd}^2 \equiv (1/2)\left(\Sigma_{ss}^2 + \Sigma_{dd}^2\right)$.

If we assume there is a contribution, δ_N, from noise we find $\delta_{\rm recon}$ is unchanged to lowest order. However the damping scale is modified. Following [15] we find

$$\Sigma_{ss}^2 \to \frac{1}{3\pi^2}\int dp\ \mathcal{S}^2(p)\left[P_L(p) + P_N(p)\right] \tag{4}$$

where P_N is the power spectrum of δ_N and

$$\Sigma_{dd}^2 \to \frac{1}{3\pi^2}\int dp\ \left[1-\mathcal{S}(p)\right]^2 P_L(p) + \mathcal{S}^2(p)P_N(p)\,, \tag{5}$$

which reduce to the expressions of [15, 16] as $P_N \to 0$. For Poisson shot-noise we expect $P_N = b^{-2}\bar{n}^{-1}$ for tracers with number density $\bar{n}$ assuming linear bias b. These equations present the generalization of the treament in [15, 16] to include shot-noise.

III. RESULTS

One method to forecast the effect of this noise on cosmological parameters constrained by BAO is to replace the Gaussian damping of Eq. (1) with Eq. (3) in the computation of the Fisher matrix for the acoustic scale s. For example, in spherical geometry [17]

$$\sigma_{\ln s}^{-2} = \frac{V_{\rm survey}}{2}\int \frac{d\mathbf{k}}{(2\pi)^3}\left[\frac{\partial P/\partial\ln s}{P+\bar{n}^{-1}}\right]^2 \tag{6}$$

with

$$P \propto D(k)\frac{\sin ks}{ks}e^{-k^2\Sigma_{\rm Silk}^2/2} + \cdots \tag{7}$$

where $\Sigma_{\rm Silk}$ is the Silk damping scale and $\cdots$ refers to terms independent of s [17]. The effects of shot-noise show up in the increased damping of the higher harmonics of the signal

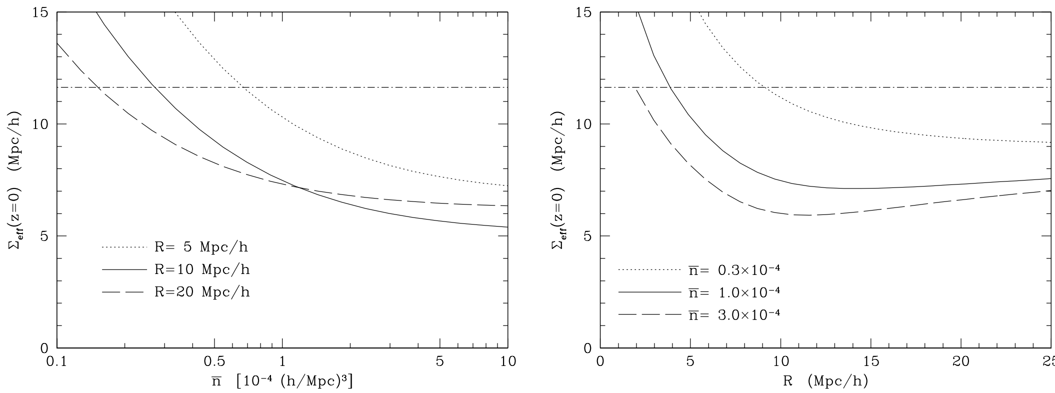

FIG. 1: (Top) The damping scale at $z = 0$, $\Sigma_{\rm eff}$, after reconstruction as a function of the number density of tracers, $\bar{n}$, assuming $b = 1$. The horizontal dot-dashed line indicates the Silk scale, or the intrinsic width of the acoustic peak, for our cosmology. (Bottom) As above but as a function of smoothing scale, R.

and the increase in the variance per **k** mode (the denominator in Eq. 6).

However, almost as much intuition can be gained by approximating $D(k)$ as a Gaussian and asking how the effective damping depends on P_N. To this end we define an "effective" Σ from the value of the damping at $k_{\rm fid} = 0.2\,h\,{\rm Mpc}^{-1}$.

Figure 1, top, shows how $\Sigma_{\rm eff}(z = 0)$ depends on $\bar{n}$ for a ΛCDM model with $\Omega_m = 0.25$. Note that reconstruction improves for higher number density tracers, but the gains saturate above approximately $10^{-4}\,(h\,{\rm Mpc}^{-1})^3$. For lower number densities, it is advantageous to use a larger smoothing scale to define the shifted field, as expected. For comparisong, without reconstruction the full non-linear smearing at $z = 0$ leads to $\Sigma \simeq 10\,h^{-1}$Mpc, scaling as the growth factor to higher redshift. The horizontal dot-dashed line indicates the Silk scale, or the intrinsic width of the acoustic peak, for our cosmology — the observed width of the acoustic peak is the quadrature sum of $\Sigma_{\rm Silk}$.

A different view is given in the lower panel of Figure 1, which shows how $\Sigma_{\rm eff}(z = 0)$ depends on R for different values of $\bar{n}$. Note the existence of an "optimal" smoothing scale, but that the minimum is extremely broad.

These results show that, within the context of Lagrangian perturbation theory, it is straightforward to understand the effects of noise in the density field on the efficacy of reconstruction. Reconstruction performs better when the density field is determined from denser tracers, but the gains saturate at $\bar{n} \sim 10^{-4}\,(h\,{\rm Mpc}^{-1})^3$. For low density tracers it is best to use a large smoothing scale to define the shifts, but the optimum is very broad.

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